CHAPTER E-8 LEVEE FLOODWALLS

E-8.1   Key Concepts – Types of Floodwalls

There are numerous floodwalls in place across the nation's system of levees. In general, floodwalls are used when there is insufficient land to place an earthen levee up to the required level of protection. They are more prevalent in urban areas where real estate is at a premium, but they may have limited use in some rural areas as well. Floodwalls are routinely constructed both within natural ground areas and also within existing man-made embankments in order to increase the existing height of protection. There are a wide variety of floodwalls, but the overwhelming majority of these are I-walls and T-walls. There are a variety of other types of walls, covered briefly in the next paragraph, but I-walls and T-walls will be the focus of this section of this manual.

Other less common floodwall types include L-walls, buttress/counterfort walls, and gravity style walls. L-walls can be assessed with similar methods as those outlined in the T-wall section of this report. Gravity walls can be assessed for stability using the general wedge methodology as outlined in U.S. Army Corps of Engineering Manual 1110-2-2100 entitled Stability Analysis of Concrete Structures (USACE, Dec 2005). Buttress (counterfort) walls are essentially T-walls with a structural member on intervals to help support the stem of the wall. These are more difficult to analyze than traditional T-walls because they have different failure mechanisms such as moment and shear failure of the buttress (counterfort) section. More information on this is covered in Chapter E-7 of this document which discusses these types of walls for dam spillway chute and stilling basin walls where they are more common due to their height.

E-8.2   General Background Information for T-walls

T-walls are one of the predominant types of floodwall in use. As noted earlier, T-walls get their name from the fact the cross-sectional area takes the general shape of an inverted "T". T-walls are generally used in lieu of I-walls when the heights required for flood protection become larger than an I-wall can safely handle which is usually in the range of 10 feet or so, although there are many exceptions to this general rule-of-thumb.   Only a review of the as-built plans will allow

you to determine whether a wall is a T-wall or an I-wall. You can't tell by simply looking at it from the ground. When the foundation conditions are undesirable, T-walls are many times pile founded for stability purposes. The piles transfer the load to better soil/rock conditions founded below the unsuitable foundation soils near the surface. In addition, many T-walls have sheetpile cutoff walls located on the riverward (heel side) to improve underseepage performance. Some T-walls may have sloped base slabs to improve global stability. Relief wells and/or toe drains on the protected side may also be present to help control underseepage. An example of a T-wall cross-section with a sloped base, taken from EM 1110-2-2502 (USACE, Sep 1989), is shown in Figure E-8-1 for reference. The external loads acting on most flood protection T-walls are usually relegated to earth and water pressures. The weight of the concrete is also considered in the global stability analysis.
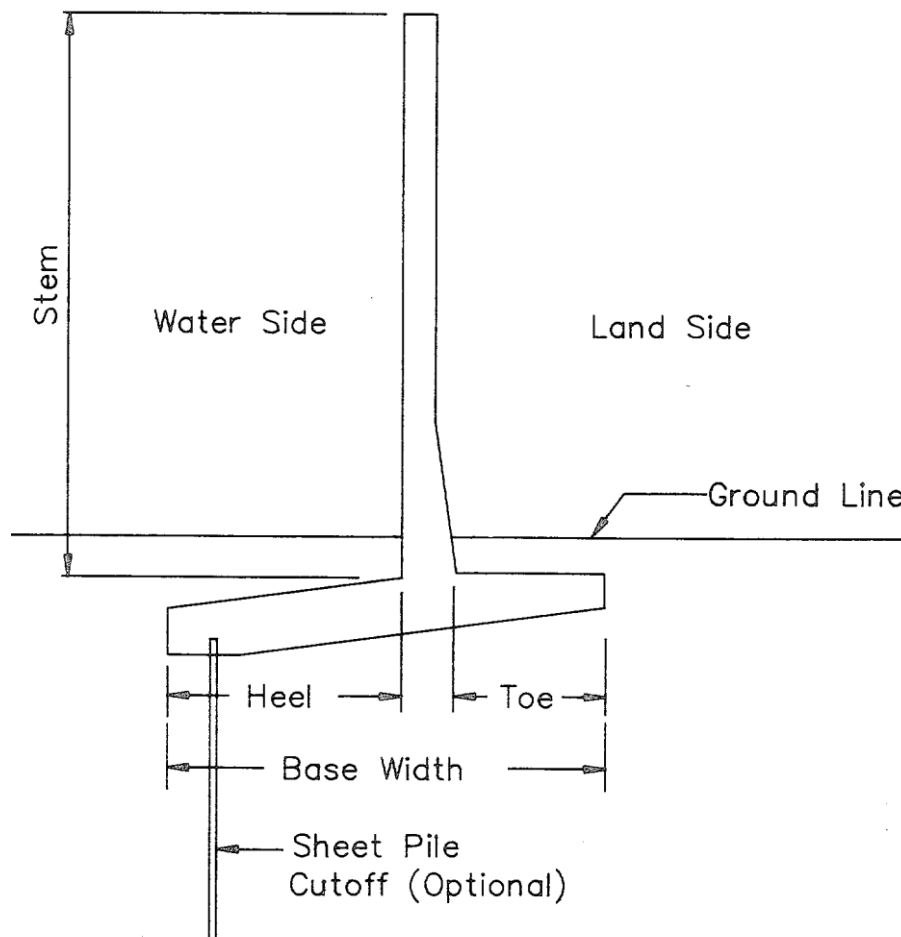

Figure E-8-1 - Example of a Sloped Base T-wall

E-8.3 General Background Information for I-walls

In general, I-walls are used when the exposed wall height is relatively short, usually less than 10 feet, but there are exceptions to this "rule-of-thumb". They are also frequently used as a transition section between levee and T-wall monoliths for closure structures. I-walls get their names from the fact that the cross-section looks like an "I". There are various styles of I-walls in use and the more prominent examples are shown in Figure E-8-2. The vast majority of I-walls within the U.S. fall into the Type II I-wall or sheetpile I-wall category shown in Figure E-8-2. The Type II I-wall is essentially the sheetpile I-wall with a concrete cap placed above the ground line.
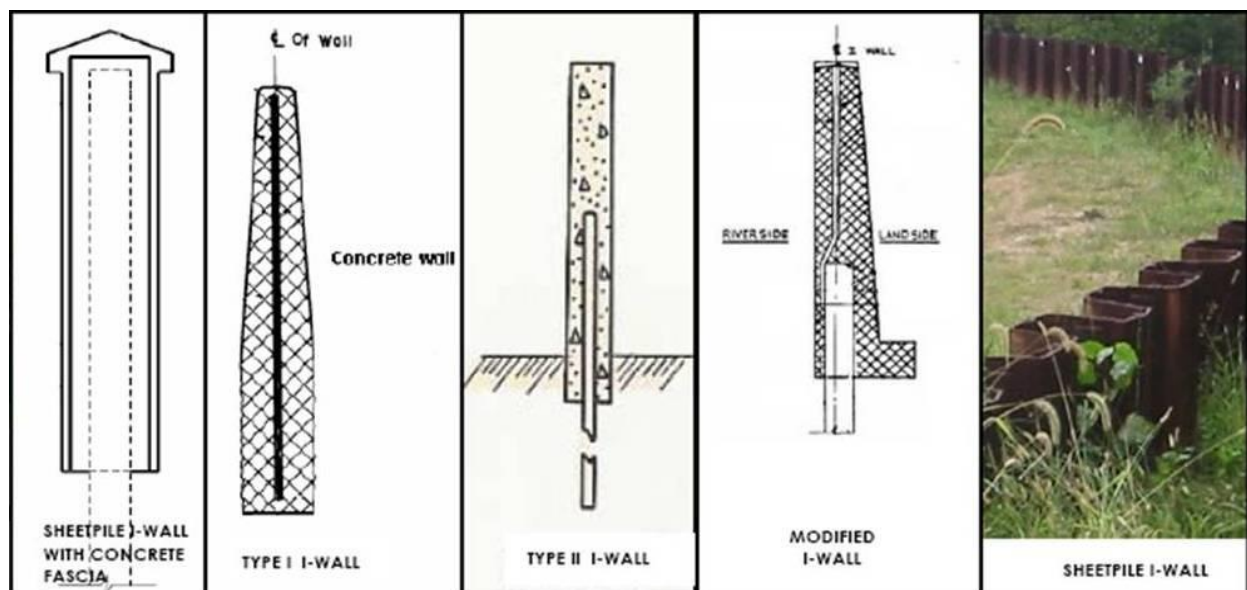

Figure E-8-2 - Example Types of I-Walls

E-8.4 External Force Computations – Soil Pressures

The computations for estimating soil pressures acting on floodwalls are covered in Chapter E-7 of this manual. Chapter E-7 covers both static and dynamic earth pressure calculation methods. While Chapter E-7 relates primarily to retailing walls, the soil pressure calculations are consistent with the approach used for floodwalls. There are some unique aspects of floodwalls, however, that are important to mention when considering the type of evaluation.

- For most levee systems where floodwalls are used in urban settings, they were likely constructed by or under the direction of the federal government and were based upon a significant historic or design flood with freeboard (additional height above the

historic/design flood elevation). For most projects, they are loaded infrequently and the combination of seismic loading coupled with an infrequent flood loading on the wall will be too remote to consider for a risk analysis. Each situation is unique and needs to be considered on its own merits, but this is an example of how design differs from risk analysis.

- For design, conservative assumptions are generally used to ensure safe wall performance. An example would be using K_o coefficient (at rest) for computing driving and resisting side earth pressures. When assessing a wall for risk analysis purposes, there may be a need to consider the use of the K_a coefficient (active) because very little movement of the wall will result in a full reduction of driving side earth pressures from the force associated with using K_o versus K_a. A good approach is to evaluate with the K_o coefficient (at rest) for both active and passive pressures and determine if there are any instability issues for the maximum water levels to be evaluated. If the analysis determines that no instability issues exist, using the more conservative K_o coefficient (at rest earth pressures) provides confidence that the wall will be stable. If calculations indicate that at rest earth pressures contribute significantly to exceeding stability limit state thresholds, then consider using active (K_a) earth pressure for the driving side. Much larger lateral movements are usually required to mobilize maximum passive resistance, especially for cohesive soils, so using full passive resistance is usually not recommended due the amount of movement required.

- Depending upon the situation, you may need to consider the potential for scour of soil around the floodwall and if this will affect your loads acting on the wall. There are two potential scenarios that should be considered. One is the potential for riverside scour which could reduce the driving load on the wall, but also reduce the seepage path under the wall as well. The other is the potential for scour of the landside toe due to overtopping of the wall. The potential for either of these should be reflected in the event tree that describes the floodwall failure mode from initiation through breach. More detailed information related to the potential for levee erosion due to river flow is covered in Chapter D-1 of this document as well as the Levee Screening Tool (LST) Technical Manual (USACE, Nov 2011). There is additional information provided related to overtopping scour below in this chapter as well as in Chapter D-3 of this document.

- If heavy rollers or specialized compaction equipment were used adjacent to the wall during construction, high residual pressures can result on the wall. There are methods to account for this situation in EM 2502 when the compaction adjacent to the wall was excessive. This is usually not a significant consideration for floodwalls with little backfill acting on them.

E-8.5 External Force Computations – Water Pressures

Water pressure at any point is computed by taking the pressure head multiplied by the unit weight of water (62.4 lb/ft^3). The pressure head is equal to the total head minus the elevation head, which represents the height the water would rise if a piezometer was placed at that location. Water pressure should be added to effective earth pressures to estimate the total pressure acting on the wall. This means the buoyant unit weight of the submerged soil mass must be used to account for the section of soil below water although this is usually minimal for floodwalls and more of an issue for retaining walls.

Additional water force provided by surge and wave action needs to be accounted for walls when that type of loading is critical to the analysis/environment. Wind speed, fetch, geometry of the embankment/wall, wall orientation, and many other factors come into play when determining the importance of surge and wave loading. An excellent source for surge/wave loadings is the US Army Corps of Engineers' Shore Protection Manual (USACE, Apr 2002) that is used for design of flood control structures in coastal environments.

Seepage below a floodwall is a very important consideration when trying to assess the likely performance of the wall. This is especially true when there is limited performance history for the wall subjected to significant flood loading. Excessive underseepage could result in sand boils or heaving on the landside of the wall. This could possibly lead to loss of wall foundation support and subsequent failure. When wall underseepage is present, the pressure head at various locations below the wall needs to be determined in order to estimate the uplift force acting against the base of the T-wall. Conservative assumptions are usually made for uplift when floodwalls are being designed, but more realistic uplift loads should be considered for risk analysis purposes.

There are several measures that are used to safely control and distribute seepage below a floodwall. Sheetpile cutoffs are added many times when there is a pervious stratum below the wall. Many floodwalls have toe drains at the landside bottom of the base slab as a means to help safely distribute underseepage and prevent the formation of sand boils. It is important to consider the potential degradation of the toe drain given its environment and operating history. Shallow trench drains may be used when the pervious stratum is not founded too deep. It essentially acts like a large toe drain. Another means of controlling underseepage is through the use of relief wells. Relief wells are intended to reduce the pressure by discharging the water but retaining the materials by use of a filter and screen. Relief wells are usually used when the pervious stratum is located deeper than what is typically handled with a toe drain system. Again, it is important to consider the effectiveness of the relief well system as their efficiency can degrade through time due to a variety of reasons. Other floodwall underseepage control measures include the use of riverside impervious blankets and landside seepage berms.

E-8.6   Water Levels for Risk Analyses

Several different water levels will likely have to be evaluated in order to develop a system response curve (probability of wall failure vs. water level) for a risk analysis. Determining which water levels to evaluate for a floodwall as part a risk analysis can be straight forward in some cases and a bit tricky in other evaluations. There are several important considerations. An estimate of the water surface profile compared to an accurate top of levee/floodwall along the line of protection will help determine how high the water will likely rise against the floodwall section being evaluated before incipient overtopping possibly occurs at another location along the line of protection. The elevation profile from the National Levee Database (NLD) can be used to help develop a top of levee/floodwall profile. This will generally be more reliable than anything provided in as-built plans since it is based upon actual survey data and will have accounted for localized settlement, construction overbuilds, etc. If there is no reliable top of levee/floodwall profile, use the best information available to complete the assessment. An assessment of the wall for water elevations slightly higher than those associated with the incipient overtopping elevation may be required, but it still may not be enough to overtop the wall for the section being evaluated. This is a particularly important consideration for long levee systems and projects that contain multiple wall and embankment sections. A few other key

points regarding selecting water elevations for risk analysis purposes are provided in the bullet list below.

- Make sure the datum being used for water surface elevation estimate is consistent with the top of levee/floodwall profile. NLD datum is usually NAVD88. Different datums have been used throughout the U.S. There are a variety of conversion tools available to determine the difference in elevations between datums.
- Ranges of loading will most likely be required for the risk analysis. Tighter ranges for water levels are typically desirable near the top of the floodwall. There is no set rule, but a good starting point might be ¼, ½, ¾, and 90% of the exposed wall height, as well as water to the top of the wall, and any intervals for wall overtopping. The term 'exposed height' refers to the height from the top of the wall to the ground/wall interface elevation on the protected side. As noted earlier, it may not be possible for the water to reach this height for the wall section being evaluated without overtopping other sections of the project so this is simply a rough guide. There may also be enough confidence in historical performance at lower elevations to know the wall will perform very well at lower water levels (¼ to ½ height range) such that assessment is not required at these levels.
- The water levels used to develop failure probabilities for the wall section need to be consistent with the levels used for the consequence estimates. A relationship of consequences (loss of life, economic damages) versus water elevation should be developed. The analysis for both the wall performance and consequences needs to cover the entire range of water elevations considered for the risk analysis.

E-8.7 Applicable Failure Modes for T-walls

There are several failure modes that are considered viable for levee T-walls, but they can generally be separated into three broad categories: global instability, strength performance, and underseepage/piping. The loading (demand) for each of the failure modes are those generated by soil and water pressures previously described. For the purposes of this document, global instability refers to overturning, sliding, and bearing capacity. Global instability failures can occur before or after overtopping of a floodwall. If the floodwall holds and then overtops, passive resistance on the protected side can be eroded away leading to global instability. The
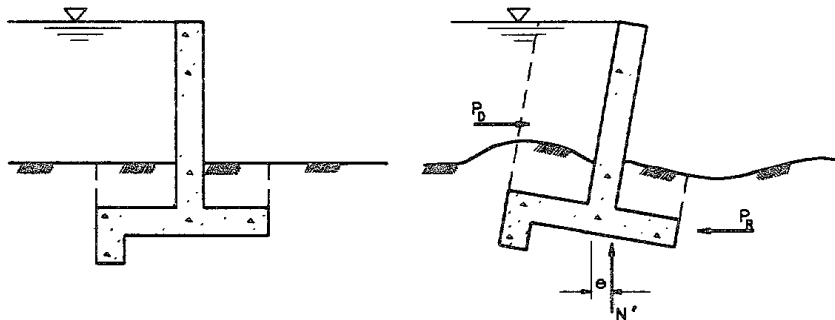
global stability failure modes are shown schematically in Figure E-8-3 (taken from Figure 4.1 of EM 2502).

Strength performance relates to excessive moment and shear forces failing the structural wall section. Underseepage and piping involves the movement of foundation soils below the wall causing a loss of wall foundation support and subsequent stability failure. The general aspects of the seepage and piping performance mode are covered in detail in Chapter D-6 of this document and the reader is referred there for best practices related to analysis methods and techniques. General considerations specific to floodwall underseepage has already been covered earlier within this chapter as part of the discussion related to water pressures acting on a floodwall.
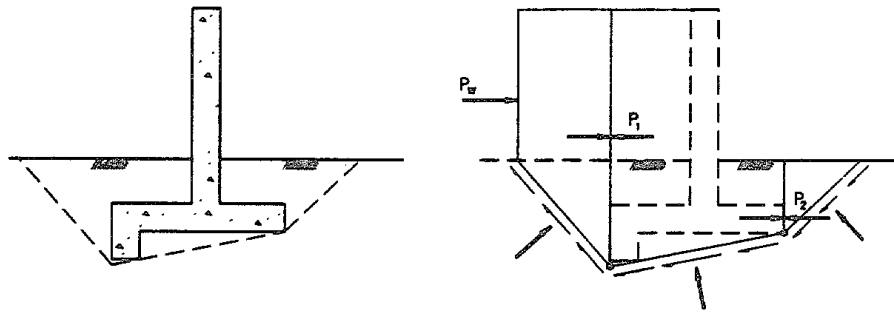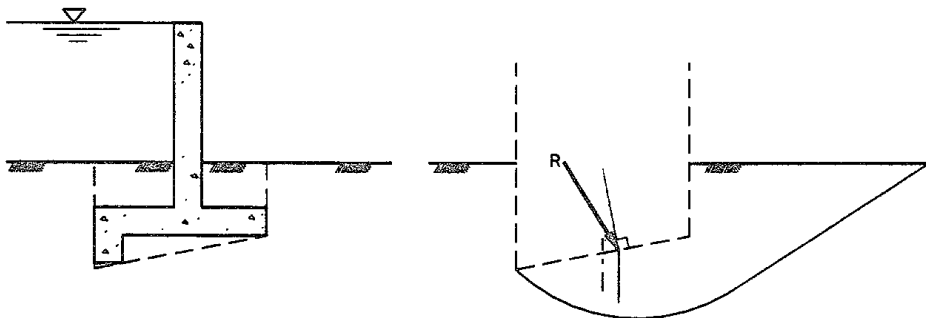
$$\text{Factor of safety} = \frac{\text{Available shear resistance}}{\text{Shear required for equilibrium}}$$

a. Sliding

Safety assessed by checking base resultant location

b. Overturning

Use bearing theory for inclined, eccentric load, sloping base

c. Bearing

Figure E-8-3 - Global Stability Failure Modes for T-Walls (Ref: EM 2502)

E-8.7.1   T-Wall Global Instability – Overturning Analysis

When assessing the overturning stability of a T-wall, you need to determine the resultant location of the vertical force acting along the base slab of the wall. You can use this information to determine how much of the base slab is acting in compression. If the resultant is located outside the limits of the base slab, then it is no longer acting in compression and the traditional limit state for overturning is exceeded. Moments are taken about the toe end of the base slab (see Figure E-8-1). Resisting moments include the weight of the structure (stem and slab), weight of material resting upon the structure, resisting soil pressure, and resisting water pressure. Driving moments include uplift, soil pressure, and water pressure. The overturning analysis may have to be evaluated for both drained and undrained soil conditions depending upon the type of soil, duration of loading, etc. Specific information related to how to assess T-walls with keys is provided in EM 2502 including examples in the appendices of that document. Remember that this is more of a design manual, but the application of the analysis method is good for risk assessment purposes when using an estimate of actual (unfactored) forces.

E-8.7.2   T-Wall Global Instability – Sliding Analysis

The same forces that contribute to or resist overturning failures also contribute to or resist sliding failures. Lateral forces (earth pressure, water pressure) push the wall in one direction or the other and vertical forces (concrete weight, soil weight, uplift, etc) either add to or take away from the normal force that supplies the frictional resistance along the sliding plane. When there is a key present the sliding resistance at the base should be calculated using an estimate of the actual shear strength parameters of the soil. Limit equilibrium is used to assess the stability against sliding. The traditional limit state for a sliding analysis is when the shear force acting along the sliding plane exceeds the shear capacity of that plane. The shear plane (slip surface) can be a combination of planes or surfaces but is usually simplified as a plane for analysis purposes. Only force equilibrium is satisfied, not moment equilibrium (which is analyzed as part of the overturning analysis).

E-8.7.3   T-Wall Global Instability – Bearing Capacity

The loading conditions used to assess the overturning analysis are used for assessing bearing capacity. The bearing capacity should be analyzed for the same plane analyzed as part of the sliding analysis, as shown in Figure E-8-3. A normal and tangent force is computed for the

structural wedge along the bearing plane. These forces are used to check the bearing capacity. The normal component of the ultimate bearing capacity is compared to the effective normal force (demand) applied to the structural wedge in a traditional limit state analysis.

E-8.7.4   T-Wall Strength Performance – Moment and Shear Capacity

The strength performance failure modes for a floodwall are caused by either excessive moment and/or shear forces acting on the floodwall. The moments generated by the forces acting on the structure need to be resisted by the floodwall. Moment resistance (capacity) is primarily supplied by steel reinforcement within the wall section. The moment capacity provided by the steel reinforcement should be checked against the moment (demand) caused by the applied (unfactored) loading. First, whether the concrete cracks should be check since if the concrete does not crack, the flexural load does not need to be transferred to the reinforcement.

The shear capacity of a wall is primarily provided by the concrete within the floodwall. This capacity needs to be compared against the shear forces generated from the soil and water loads. Whether the concrete cracks due to the moment (demand) will need to be taken into consideration as this will impact the shear capacity of the concrete. When steel shear reinforcement is provided, the shear capacity will be a combination of the steel reinforcement shear capacity and the concrete shear capacity.

E-8.8   Special Considerations for I-walls

I-walls warrant special consideration in light of their performance during Hurricane Katrina in New Orleans. Several Type II and sheetpile I-walls failed under load during Hurricane Katrina for different reasons. Some of these walls were overtopped and the protected side was exposed to flows from waves and storm surge causing erosion near the base of the protected side of the wall and subsequent instability. Wall deflection and foundation issues of other I-walls in New Orleans caused them to fail prior to overtopping at other locations. Detailed field investigations, computer analysis, and laboratory modeling following Hurricane Katrina concluded initial wall deformation formed a small crack between the base of the wall and the levee soil on the flood side. This, in turn, caused a full hydrostatic head to be loaded on the face of the wall down to the depth of the crack. The combined I-wall/embankment sections were not designed for this loading condition. The increased load on the composite I-wall/levee section essentially failed the

levee through a combination of stability and under seepage of the protected side of the levee. The details of these failure modes are described in the Interagency Performance and Evaluation Team (IPET) report on the levee system response during Hurricane Katrina (USACE, Jun 2009). The reader is encouraged to read the IPET report if more detail is desired.

As a result of the performance of I-walls from Hurricane Katrina, the U.S. Army Corps of Engineers began a multi-phase investigation of their inventory of I-walls to assist in writing new guidance for their design and analysis. This resulted in the development of USACE Engineering Technical Letter (ETL) 1105-2-575 "Evaluation of I-walls" (USACE, Jun 2011). The information provided herein summarizes important analysis considerations and procedures from that document. The reader is encouraged to read the reference document if more detailed information is desired. Appendix B of ETL 575 provides criteria for stability and seepage evaluation of existing I-walls. Key points of ETL 575 are as follows:

- Failure modes evaluated should include rotational instability, translational/deep-seated instability, and seepage
- Rotational instability was found to be the dominant failure mode for wall sections analyzed as part of the I-wall Phase III evaluation program
- Translational instability was found to be the controlling failure mode for I-walls founded on soft clays found in the New Orleans area as well as a full scale load test conducted with a stiff clay over a soft clay
- Both drained and undrained soil properties may need to be used in the analysis depending upon the site-specific conditions
- The soil-sheetpile gap analysis is associated with undrained soil conditions
- The USACE program CWALSHT is a freely accessible and easy-to-use analysis program that can be used for analysis of drained soil conditions. Other considerations need to be taken into account for undrained soil conditions when using CWALSHT.
- CWALSHT may overestimate the resistance provided by compact clay levees on soft foundations and a methodology has been developed within Appendix D of ETL 575 (USACE, Jun 2011) to adjust these pressures accordingly.
- Wall friction can play an important role and should be included in the analysis of I-walls

- Underseepage performance of the I-walls in New Orleans were important contributors to their performance because of the soil conditions (sand foundation overlain by fine-grained marsh deposits)

- A variety of I-wall, soil/drainage condition analysis procedures are provided with ETL 575 for reference.

- A detailed evaluation I-wall flowchart covering different steps in the analysis for varying soil conditions is provided in Appendix E of ETL 575.

The analysis methods and techniques provided in ETL 575 are a great reference source and when assessing I-walls for performance, the reader is encouraged to use this document. It is important to note, however, that ETL 575 is not designed to be reference document for risk analysis. Some of the guidance criteria and information within ETL 575 was developed with reliability analysis methods, but the document does not provide information on how to assess an I-wall as part of a risk analysis. Therefore, any I-wall analyses developed using the methods outlined in ETL 575 should be used as supporting information for expert opinion elicitation of an experienced panel of engineers to develop probabilistic performance values. The panel should include structural and geotechnical engineers familiar with I-wall analysis techniques and historical performance.

E-8.9   Floodwall Performance Other Considerations

E-8.9.1   Overtopping

Overtopping of a floodwall without the wall failing is not really a "failure" of the wall as it is simply a function of what level of protection the wall provided; thus, the wall performed its intended function but was simply not constructed high enough to contain the flood event. Additionally, floodwalls that are overtopped and subsequently failed likely performed their intended function since they held for water elevations up to the top of the wall, but if the failure occurs after overtopping then impacts can be more severe. Having floodwalls resilient to overtopping can reduce the risks associated with overtopping events for some flood protection projects. Depending upon the erosion resistance of the landside soils, failure can occur quickly following overtopping or it could sustain substantial overtopping without failing. If the soil has little erosion resistance, it is possible that damaging landside scour and subsequent wall failure

could occur simply due to wave overwash. There are several factors that are important to consider when evaluating overtopping risks including the exposed height of the wall, duration of the event, and type of soils on the landside face of the wall. Figure E-8-4 shows a failed sheetpile I-wall that overtopped and quickly and failed, whereas Figure E-8-5 shows a Type II I-wall that suffered significant overtopping without failing. Some walls have been designed to be more overtopping resilient by adding scour protection on the landside and transition zones between levee embankment and wall sections as shown in Figure E-8-6.

Figure E-8-4 - Failure of Sheetpile I-wall due to Overtopping

Figure E-8-5 – Overtopped Type II I-Wall with Damage but No Failure

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Figure E-8-6 – Overtopping Scour Protection for Sheetpile I-wall

E-8.9.2   Vegetation

The presence of trees and significant vegetative growth immediately adjacent to floodwalls has the potential to adversely affect stability of floodwalls in a variety of ways. This could be vegetation on either side of the wall. A 'safe distance' needs to be provided from the foundation of the wall to any significant vegetation; unfortunately, there is no 'preset' safe distance that will account for all situations and each must be judged in the context of how a tree might adversely affect floodwall stability in its given environment. The 15-ft vegetation free zone within USACE guidance is specific to maintenance and inspection requirements. This distance is not necessarily indicative of how vegetation may affect floodwall stability and should not be taken as such. There are instances where certain types of vegetation within 15' may not be harmful to the performance of the floodwall, just as there are instances where vegetation greater than 15' away from the floodwall's foundation could potentially fail the wall. Careful engineering judgment is required to evaluate each situation on its own merits.

When large trees and/or trees with significant root systems are located in the vicinity of floodwalls, careful consideration should be given to how they might adversely affect performance. A few situations to consider are provided below.

- Trees with large root systems extending below floodwalls have the potential to 'jack' or lift the wall potentially causing a wide range of failure issues such as cracking, separation of joints, or wall failure. An example of a situation of this is shown in Figure E-8-7.
- Large trees adjacent to walls can topple over and structurally damage a wall particularly when surrounding soils are already saturated from heavy rains and flooding (see Figure E-8-7).
- Floodwalls with toe drainage systems in place to relieve uplift pressures for wall stability can be damaged either by tree roots penetrating the toe drain system or having an uprooted tree dislodge the drainage system rendering it ineffective.
- Floodwalls requiring passive resistance for stability can also fail if a large soil mass on the protected side is removed by an overturned tree.

E-8.9.3   Encroachments

Similar to the situation with trees, encroachments can also have a negative impact on floodwall performance. For the purposes of this manual, an encroachment is when a feature (building, telephone pole, fence, etc) is placed adjacent to a levee embankment or floodwall section that can potentially have an adverse impact on performance. The most damaging encroachments with respect to floodwall performance typically involve those associated with an excavation on the protected side of the wall. This can cause loss of lateral support, an increase uplift forces, and overall stability issues. Similar to trees adjacent to floodwalls, there is no preset clear distance that is considered satisfactory for all situations. Each situation is unique and requires assessment on its own merits. The LST Technical Manual (USACE, Nov 2011) provides a good overview of situations where encroachments warrant concern for both levee embankments and floodwalls.

Figure E-8-7 – Large Trees Adjacent to Floodwall

E-8.9.4   Pipes

Deteriorated culverts/pipes/utility lines below the foundation of floodwalls are a cause for concern regarding underseepage and piping of the floodwall's foundation. This is particularly true for pipes that are constructed of materials likely to degrade over time and are not routinely inspected to determine their actual condition. A defect through a pipe below a floodwall can lead to a preferred seepage path and depending upon the conditions (surrounding soil, loading duration, etc) can cause piping of foundation materials through the defect. This can cause a loss of foundation support for the floodwall and lead to wall instability and failure of the structure. Defects can occur either through the body of the pipe (perforations) or at separated joints. A thorough review of the as-built plans and permits needs to be done in order to determine if and where pipes cross below floodwall sections of the project. Deteriorated pipes running parallel to floodwalls can also be an issue if they are close enough to adversely affect performance from an underseepage or stability standpoint. The LST Technical Manual (USACE, Nov 2011) provides a detailed narrative on adverse environments for various types of pipes and is a good resource to determine if pipe is likely to be an issue from a performance standpoint.

E-8.9.5   Barge Impacts

Levees which are located in heavy commercial traffic waterways could be at risk of being impacted by loose barges. The risk of barge impacts is present during both flood events and normal water levels, but is likely the greatest during flood events. During such events it is common for the coast guard to shut down traffic on the waterway, requiring tows to tie off at mooring locations. High flows can cause the tow lines between barges to break allowing the barge drift downstream. The uncontrolled barge is then at the mercy of the current and could drift into the levee. Levees which are located near mooring facilities are at a greater risk of barge impacts. Depending on whether the barge is loaded at the time it breaks loose could dictate how high on the wall an impact could occur and with what force. An unloaded barge is not likely to have much draft and will likely impact the wall above the water line. While a loaded barge is likely to have a draft placing the top of the barge near the water line which is where the impact is most likely to occur on the wall. An unloaded barge does not have as much weight as a loaded barge which could reduce the impact force comparatively. An unloaded barge, however, could be traveling at faster speeds which would tend to increase the impact load

compared to a loaded barge. An impact from either a loaded or unloaded barge could impart a large impact force that could cause a failure or severely damage the wall. Figure E-8- 8 below shows an example of an uncontrolled barge that impacted an I-Wall during Hurricane Katrina.

Figure E-8- 8 – Example Damage from a Barge Impact During Hurricane Katrina

E-8.10 Levee Floodwall Event Tree

Three example event trees for a risk analyses of a levee floodwall are shown in Figure E-8-9 to Figure E-8-11 near the end of this chapter. The first event tree lays out the path from initiation to breach related to a global failure of a T-Wall. This event tree considers the potential wall overtopping as well as whether any erosion of the landside toe occurs if overtopping does occur. The second event tree shown is related to a strength failure of the wall stem for a T-Wall. The event tree considers the potential for the wall fail either due to shear of the concrete, yielding of the reinforcement or excessive deflection. The third event tree presented is related to failure of an I-Wall. Branches associated with the seepage/piping under either a T-Wall or I-Wall are not

depicted for clarity. The reader is encouraged to review Chapter D-6 for more details associated with 'typical' branches for seepage and piping failures. It is important to note that exceeding the limit state for global instability or excessive moment/shear does not necessarily lead to breaching of the floodwall. There are usually additional resisting forces, such as side friction between monoliths, which are not considered as part of simplified 2D analysis. These additional resisting forces should be considered as part of a risk analysis, however, if they are likely to exist in reality. Analytical computations from a Monte Carlo risk analysis model can be used to help statistically estimate probabilities and probability ranges for branches associated with limit state exceedence. Elicitation-based approaches are usually used for estimating branch probabilities for branches following the limit state branches.

E-8.11 System Response Curve Development

An example T-wall with a graphical system response curve is shown in Figure E-8-12 at the end of this chapter. The system response curve is developed by estimating each failure path probability (multiplying the individual branch probabilities along each failure path). If there are multiple failure modes which could result in a beach due to similar loadings, a common cause adjustment might need to be applied in order to not overestimate the risk. It is not uncommon for common cause adjustments to result in small reductions in the risk estimate and add a level of complexity to the risk estimate calculation without changing the conclusion. Omitting the common cause adjustment would be conservative and should be considered on a case by case basis. The floodwall system response curve shown in Figure E-8-12 is being assessed for water levels above the top of the wall. Some assessments will require this level of detail if overtopping with and without breach needs to be considered.
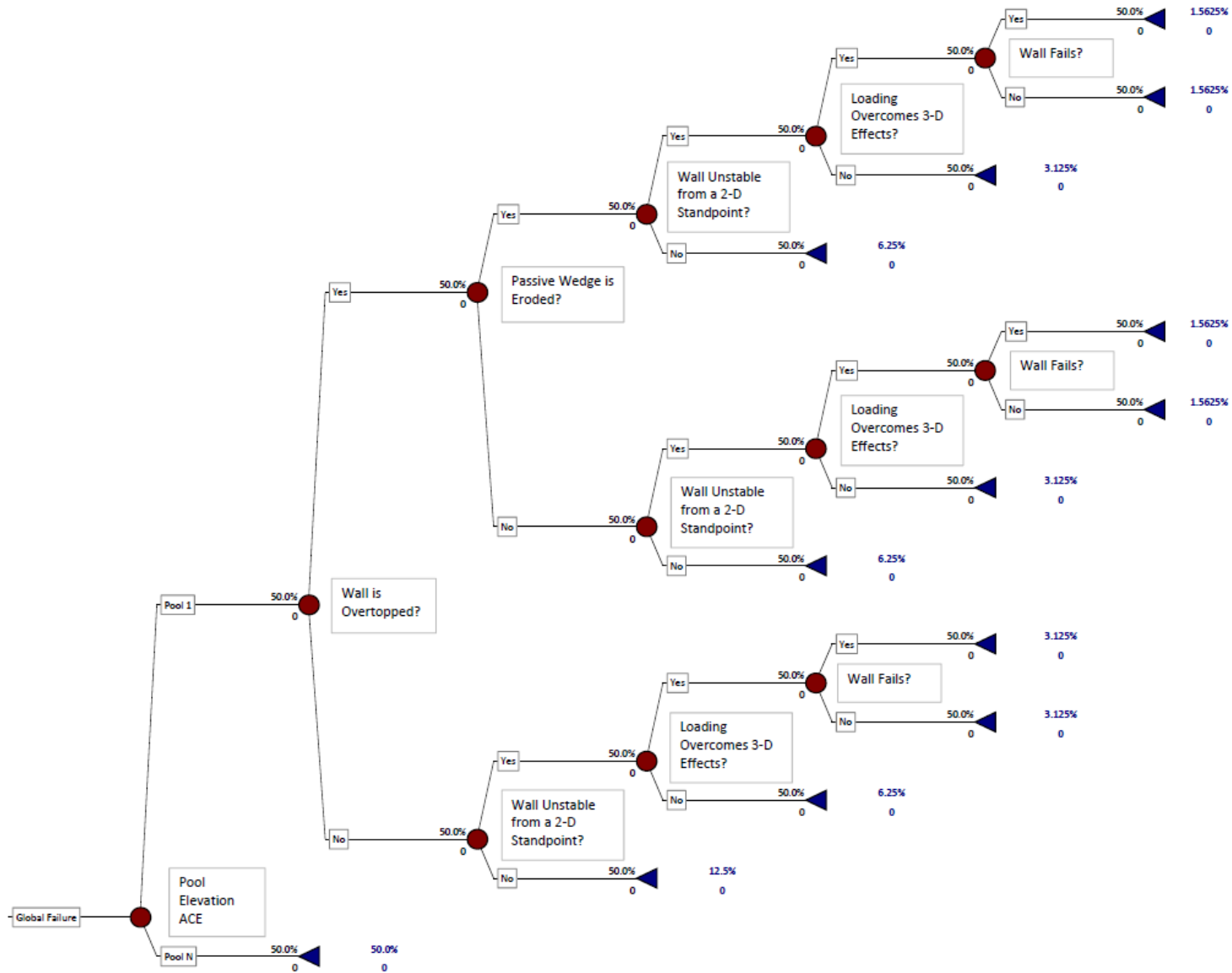
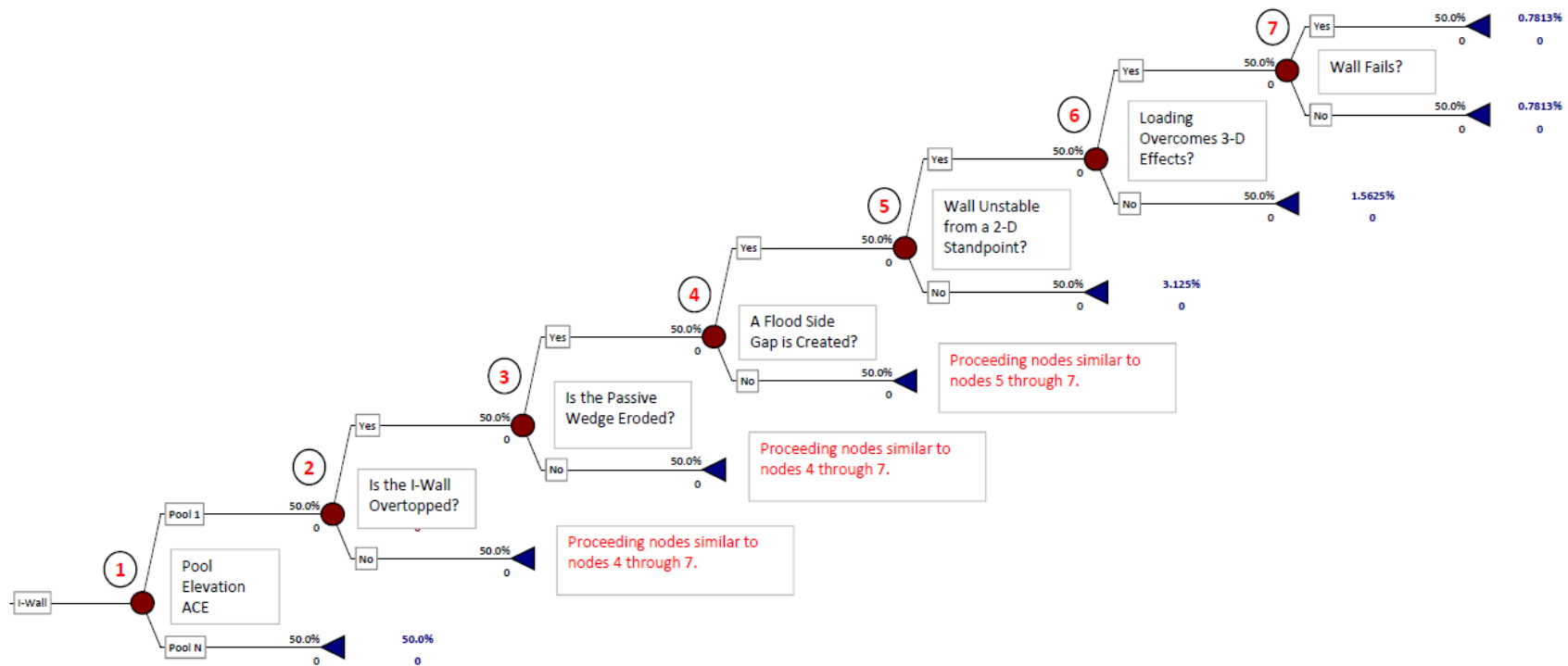**Figure E-8-9 - Example Event Tree for Global Stability Failure of T-Walls**

E-8-21

Figure E-8-10 – Example Event Tree for Strength Failure of a T-Wall

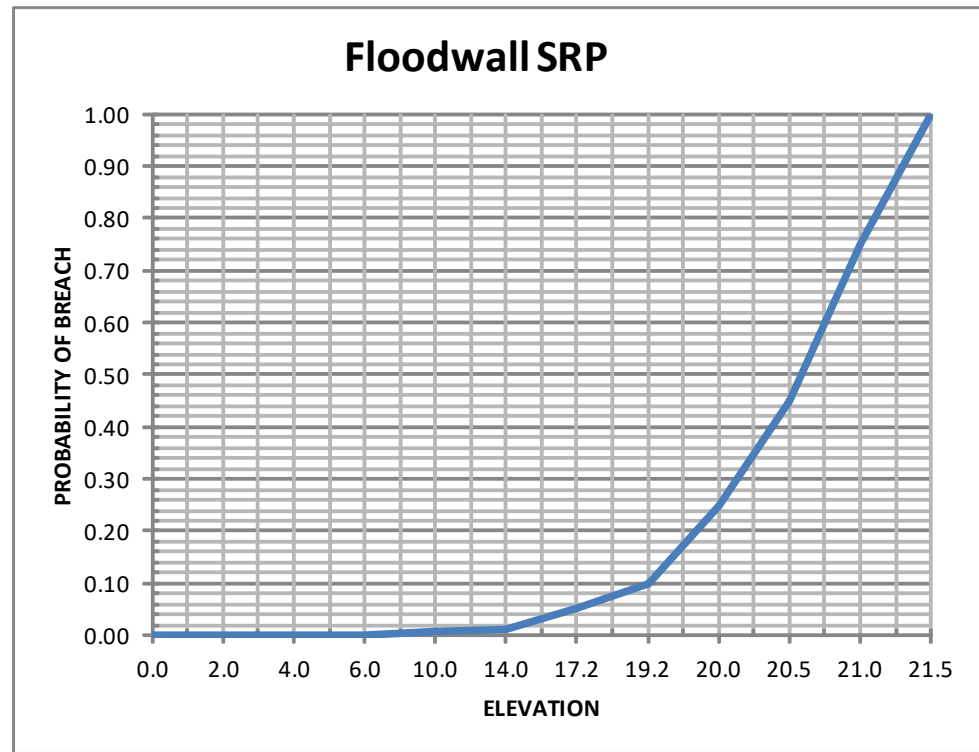**Figure E-8-11 – Example Event Tree for Failure of an I-Wall**
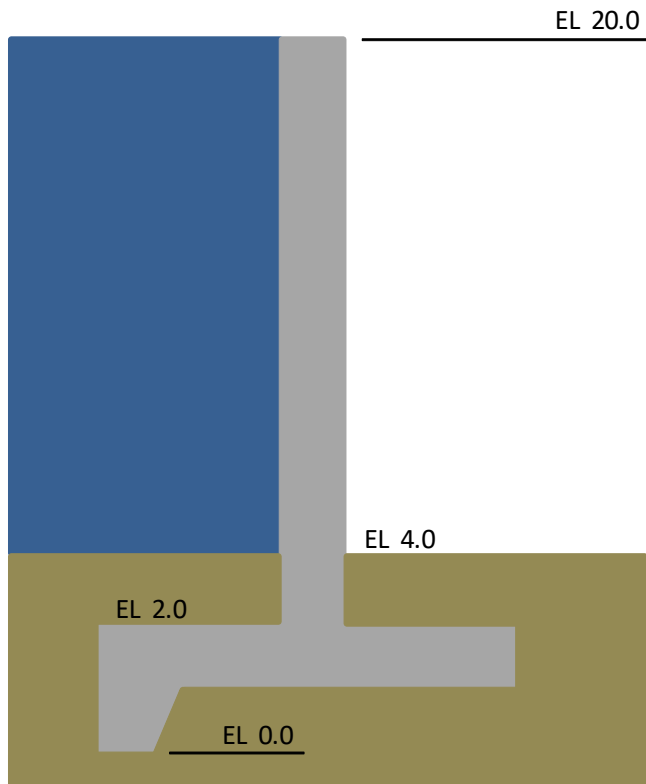
Figure E-8-12 – Example System Response Curve for Levee Floodwall

E-8.12 References

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